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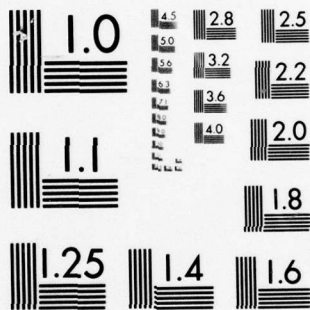
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ZERO ORDER DIFFRACTION DISPLAY SYSTEMS

B. R. Clay
B. E. Hendrickson

FINAL REPORT

MARCH 1978

PREPARED UNDER CONTRACT N00014-77-C-0786

FOR

OFFICE OF NAVAL RESEARCH

BY

RCA/GOVERNMENT SYSTEMS DIVISION

AUTOMATED SYSTEMS

BURLINGTON, MASS.

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I. INTRODUCTION

The purpose of this program is to examine the relative attributes of ZOD (Zero Order Diffraction) microimages, FIH (Focussed Image Holograms) holograms, and Standard Ektachrome (EK) material for application to high brightness displays. Specific comparisons of brightness, resolution, contrast, and colorimetry were made using a breadboard viewing screen system allowing simultaneous side-by-side projection of the three media. Typical subject matter included aerial maps, resolution, and color bar charts.

II. COMPARISON OF TECHNOLOGIES

ZOD microimage technology was recently developed by RCA Research Center in Zurich, Switzerland. The distinguishing characteristics of conventional color, ZOD, and FIH projectors are shown in Figure 1.* (A discussion of the ZOD technology is presented in Appendix 1.) A brief summary of the advantages of ZOD microimages relative to color film and FIH material is given below.

ZOD vs. Color Film

The primary difference between ZOD microimages and conventional color slides is the method by which light passing through the slide is modulated. Conventional color slides store information in several layers of color dyes which selectively absorb unwanted light, converting it to heat. This heat generation within the color slide represents a fundamental limit to the maximum intensity employed in any projector and, therefore, to the maximum brightness of the display.

In contrast, ZOD microimage slides store information in the form of surface corrugations which diffract unwanted light out of the system where it is absorbed by the walls of the projector. Since ZOD slides absorb negligible amounts of projector light energy, it can accept a high level of illumination without fading or incurring physical deformation due to heating.

* Standard Ektachrome and ZOD slides require a single light source to project a color image. Color reproduction using FIH technology typically utilizes six lamps.

ZOD vs. FIH

Both ZOD microimages and FIH slides employ non-absorptive phase gratings to impress information on an optical wavefront. A lens is used to image the modulated wavefront. The basic difference between the phase gratings of the ZOD microimages and FIH slides is that the ZOD grating diffracts unwanted light out of the system, whereas an FIH slide diffracts wanted light into the system (Figure 1). Although this may appear to be a trivial difference, the consequences have beneficial effects on image brightness, player complexity, and stability requirements for the ZOD microimage recording equipment.

III. MEASUREMENT TECHNIQUES AND APPARATUS

The projection test stand shown in Figure 2 was assembled in order to compare the significant parameters of the ZOD, FIH, and Ektachrome (EK) slide technologies. Channel A projects the FIH slide, channel B the EK slide, and Channel C the ZOD microimage. Side-by-side projection of the three slide media facilitated a comparative subjective evaluation of image quality. Each channel employed identical $f/4$ projection lenses. Magnification of the recorded image was 17X for each channel.

The ZOD and EK channels each employed a single GE 1962, 60 watt projection lamp. The FIH light source assembly consisted of three pairs of lamps. Input power to each channel was monitored by a wattmeter (Weston 432) switched into the supply circuitry for each lamp or lamp assembly. A Variable Transformer was used to control the input power to each channel.

The images derived from the ZOD and EK slides were projected on directional screens constructed as shown in Figure 3a. FIH images were projected using similar optics but with the source arrangement shown in Figure 3b. For all three systems, lenses L_1 and L_2 form an image of the exit pupil of the projection lens L_3 , in the observer plane $00'$. The focal plane of L_2 contains the second principal plane of L_3 . Reflector R images the lamp filament at P. For the FIH system the diffractive action of the storage hologram produces an image at the point P' . Thus, an optimum brightness match is obtained from the lamp to the observer plane. In order to

cause each image element to cover all points in the observer plane bounded by the circle 00' (the designed observer relief area), the screen surface is covered with lenticules of a diameter of the order of a resolution element. Each lenticule has a focal length which causes the light to diverge to a ten inch circle at a 30 inch viewing distance and each lenticule f-number is such as to match the system f-number.

Light level at the projection screen was measured using a luminance-weighted photometer (Weston 759).

IV. BRIGHTNESS

The relative brightness of each display medium was determined by measuring the brightness efficiency (BE) of each channel. Brightness efficiency is defined as the screen luminance divided by the input power to the projection lamp (foot-lamberts/watt). The higher the BE, the more efficiently optical energy incident on the slide is transferred to the screen in the form of useful display information.

Since the optical density and colorimetry of Ektachrome slide material will vary with exposure, a series of Ektachrome duplicates of a ZOD slide containing a color test pattern was produced. Exposure of the Ektachrome duplicates was varied about the optimum in increments of 1/2 f-stops. A group of five subjects then viewed the EK duplicates and ZOD original at equal brightness in the test stand. Subjects were asked to determine the best color match between the ZOD and EK slides. The brightness efficiency of the EK slide selected by the majority of subjects was then measured and compared with that of the original ZOD microimage and that of an optimally exposed white FIH hologram. The results of this experiment are given in Table 1 below.

TABLE I
HIGHLIGHT BRIGHTNESS EFFICIENCY

Medium	Highlight Brightness Efficiency (FL/W)	Relative Brightness Efficiency (FIH=1)
FIH	.08	1
EK	.43	5
ZOD	.85	10

Table I indicates that for a given input power a ZOD microimage slide would produce a display brightness 10X that of an FIH display and 2X as bright as an EK display. Note, as described below, this is not an indication of the maximum luminance obtainable with any of the media.

The three layer ZOD technology of the three technologies considered is capable of producing the brightest image, i.e., highest luminance. Both the FIH and ZOD technologies remove power density limitations at the storage plane imposed by the absorptive dyes of color films. For the case where the storage densities are the same, the ZOD hologram will be 3 times the brightness of the FIH hologram and conservatively 4 to 5 times the brightness of color film.*

The difference between these factors and the brightness efficiency factors of Table I lies in the nature of projection systems. Table I describes brightness efficiency, i.e., foot-Lamberts/watt; the factors above are based on the maximum power density that can be concentrated on the active area of the storage medium. The power densities are related to source size, collection efficiency and allowable power density in the storage medium and are not defined on the basis of normalizing source power.

Consider the relationship between the ZOD and FIH holograms. Assume both holograms employ the same source with the same collector efficiency. Operating the source optimumly, i.e., a high density source, high temperature and an optimized collector assembly, allows maximization of the energy density over the active area of the storage medium. (It is the density from a single source that is assumed to be 2 to 3 times larger than can be tolerated by color film.) The FIH system with its

* More experimental data beyond the scope of the current program with regard to the fading characteristics of color film at high energy densities is required before this factor can be defined with certainty.

source has a transmission efficiency through the medium approaching 100% (neglecting surface reflection losses). It utilizes the total visible spectrum of the radiated energy and as a consequence, has a source spectral efficiency approaching 100%. The FIH technique on the other hand, uses 6 lamps having a collection assembly that is the same as that for the ZOD system. However, each lamp is employed to form the paired red, blue and green readout beams. In addition, the three superimposed FIH holograms have a peak white diffraction efficiency of 20%; only 20% of the energy falling on the hologram is directed to the collection aperture of the imaging lens. As a consequence, the maximum brightness of the system is 36% ($6 \times 0.2 \times 0.30$) of the ZOD image.

As previously discussed, the lack of color absorptive dyes in ZOD microimages will permit the use of extremely bright projection sources without bleaching. The extent of this phenomena in Ektachrome material may be seen in Figure 4. The slide shown was placed in a Kodak Carousel 550 projector for 18 hours. The lower half of the slide was shielded from exposure to the projection lamp. Significant bleaching may be seen in the unshielded portion of the slide.

V. RESOLUTION

Projection of a ZOD microimage requires that the zero diffraction order be transmitted by the projection lens and that all higher orders fall outside the lens aperture. This requirement is met if the period d , of the diffractive structure is sufficiently small such that

$$d < \lambda / 2 \sin (\epsilon / 2) \approx \lambda \cdot (f\text{-number})$$

where

λ = the shortest relevant wavelength

ϵ = angular aperture of lens

For a typical projector with an f-number of 2.8, this implies d must be less than $1.4 \mu\text{m}$. The spatial frequency of the FIH fringe pattern is not constrained by this consideration and is 100 cycles/mm.

The maximum resolution obtainable in a single grating structure is determined by the choice of grating period. For $d = 1.4 \mu\text{m}$, the grating frequency is 714 lp/mm. The maximum resolvable picture element would be half this fundamental frequency or 357 lp/mm. Figure 5 shows an estimate of MTF characteristics of ZOD microimages and typical color films. The range of values indicated for ZOD microimages is a function of the phase relationship of the grating structure of the screened picture element being reproduced.

For the purpose of evaluation, a resolution chart was recorded in the FIH and EK format. A 3 layer, 4 surface ZOD resolution chart was also recorded. The ZOD slide consisted of three primary grating structures created from three screened color separations of a color original. The black and white information representing the resolution chart was included by embossing another surface consisting of a crossed sine wave pattern, on the back of the middle primary grating.

The maximum resolution obtainable on the viewing screen using any of the display media is dependent on the screen resolution and the MTF of the projection lens. The sinusoidal MTF of one of the projection lenses was measured on an Ealing/Eras 100 and is shown in Figure 6. The 20% lens response occurs at approximately 80 lp/mm. Since this was far below the theoretical resolution of the ZOD (see Figure 5) and FIH slides, slide resolution was measured visually by examining each slide under high magnification.

Figures 7 through 9 are photographs of each of the slide materials (FIH, EK, ZOD) under various magnifications. Numerical scaling in the photographs themselves is relative and should not be construed as an absolute measure of the slide resolution.

Figure 7 shows the FIH resolution test pattern slide at a magnification of 63 (when the circle of the viewing aperture is scaled to a 3.15" diameter). The photograph indicates the FIH hologram is capable of recording spatial frequencies in excess of the maximum spatial frequency of the test pattern, 150 lp/mm. As can be seen from the photograph, all lines were strong, suffering no perceptible degradation in the recording process.

Resolution of the EK slide (Figure 8) is well below that of the FIH or ZOD as anticipated. Magnification of Figure 8 is 56 (when the circle of the viewing aperture is scaled to 3.3" diameter). Grain structure is apparent throughout the photograph. The "80" line pattern, corresponding to 71 lp/mm, was judged to be the limit of resolution.

Figure 9 shows the ZOD microimage at a magnification of 221 (when the diameter of the viewing aperture is scaled to 3.15"). The limit of resolution is circled in the photograph.

This pattern corresponds to 225 lp/mm on the slide material. Structure is visible in patterns whose spatial frequency is considerably higher than the resolution limit. The grating period of this slide was $d = 1.4 \mu\text{m}$. A brief summary of the measured resolution of ZOD, FIH, and EK slides is given in Table II below.

TABLE II
MEASURED RESOLUTION OF VARIOUS DISPLAY MEDIA

Ektachrome Slide	71 lp/mm
FIH	>150 lp/mm (limit of resolution chart)
ZOD Microimage	225 lp/mm

The determinations made above were as the result of measurement at the storage scale. To place this information in context, existing color film displays and RCA's FIH display project the stored information with a magnification of 20 to 25, resulting in limiting resolution at the display screen as shown in Table III.

TABLE III

EK Slide	3.55 to 2.84 lp/mm
FIH	>7.5 to 6.0 lp/mm
ZOD Microimage	11.28 to 9.0 lp/mm

To further describe the significance of the resolution characterization, it is noted that the human eye, at a viewing distance of 30 inches, that specified for cockpit display systems, is capable of resolving 4.5 lp/mm. Based on this observation, EK slides for the scaling selected appears marginal; the image will and does appear soft when viewed at the 30" distance.

While the ZOD system offers the potential for high resolution, it also presents a fabrication problem. The measurements conducted above were done so on a single layer of the multilayer ZOD hologram.

As described in Appendix I, the developed ZOD technique employs three superimposed micro image gratings to produce color images. This color rendition which is subtractive in nature, employing cyan, magenta and yellow primaries, is discussed in the next section. The use of three colors requires, in order to obtain high resolution, a precise registration of the three color separations. The nature of the ZOD process is such that each element of the three element separation set be recorded as a relief representation on the surface of a thermal plastic storage medium. The three surfaces must then be precisely registered. A pinning system has been used in the past to accomplish this precise registration. This method, as well as a variety of alternate methods, should be evaluated to establish the most effective method of registering the separation elements so that registration will be maintained when the film is employed in a high speed retrieval system.

There is a possible alternative method of recording the high resolution image information compatible with the ZOD technology. It is possible by utilizing a basic cross sinusoidal grating to produce black and white image storage on a single surface. Such a grating structure used in conjunction with the primary color system, may provide a technique that greatly simplifies the resolution requirements. High resolution black and white information could be recorded on a fourth layer containing the crossed sinusoidal grating while the color information is recorded at lower resolution using the subtractive color gratings.

Both the method of precise registration for the three color system, and the

advantages to be gained by employing the black and white information recording need to be evaluated to determine which method is preferred to utilize the inherent high resolution of the ZOD system.

The FIH and color slide film are not affected by the requirement to register multilayers - at least not in the same fashion as the ZOD technique. Color film is a multilayer film. The three layers required for color rendition are applied to a common substrate. The layers are exposed at the same time and through the same optics.

The basic resolution of the color film is restricted by this recording operation and the fact that the layers are separated and as such are difficult to focus, both during recording and during playback.

The FIH system allows recording of three element separation sets in a common area on one surface⁽¹⁾. Precise registration is obtained by a pinning operation at full scale. The registration process is built into the recording operation and as such does not require precise registration of film layers.

Both the FIH and color film processes are continuous tone processes. The transmission of color film over a particular color is to a first approximation inversely proportional to the exposure within that band. Similarly, the diffraction efficiency of the FIH hologram is proportional to energy in the object beam used to make the recording.

The ZOD hologram on the other case, is a binary system. The gratings are designed to either transmit or block the three subtractive primaries when the square wave color grating systems are employed, or the total visible spectrum in the case of the crossed sinusoidal grating. To obtain continuous color or gray scale, it is necessary to resort to a screening process similar to that used by the printing industry. This in effect provides a limitation on system resolution.

(1) "HHSD Demonstration Model Development", Final Report Contract N62269-76-C-0890, December, 1977, RCA-Burlington

For ZOD gratings recorded at 714 cycles/mm, the screening frequency should be one-half the grating frequency, or 357 cycles/mm. Similarly, the basic information frequency should be one-half the screening frequency.

This then implies that a maximum information rate of 178 cycles/mm ($\frac{714}{4}$) at the storage scale, or 8.9 to 7.12 cycles/mm at the display scales (20X to 25X) of the reference map system. A value that is considered to be more than adequate value for 30" viewing.

VI. COLORIMETRY, CONTRAST, IMAGE QUALITY

Most evaluations of colorimetry are subjective in nature, i.e., we perceive color via a complex interplay involving sensors within the eye and an evaluation process occurring within the brain. The transition from radiant energy to visual stimuli (photopic) is accomplished by three sets of cones, each set having an individual response in the red, blue, and green portions of the visible spectrum. The eye evaluates the brightness of the image by summing the response of the three receptors, while the brain determines chromatic attributes by a process that involves ratioing the various stimuli. The exact nature of the ratioing process is not completely understood.

Any display system should use, to best advantage, the subjective nature of the color visual system to convey information. Basically we desire a bright display with a resolution high enough to ensure overall system performance which is limited primarily by the eye. Human judgment as to the fidelity of color is based solely on the memory of what certain objects should look like (e.g., a yellow banana, blue sky). For this reason the most pleasing or informative picture may not have colors which exactly match those of the original scene. The fidelity requirement is further reduced when dealing with abstract information such as that present in a color map. The only requirement is that the map colorimetry convey meaningful characteristics of the terrain.

The range of colors obtainable using ZOD microimages and FIH technology has been plotted on the CIE chromaticity diagram shown in Figure 10. Also indicated is the approximate range of colors obtainable using printers inks. The ZOD microimage produces approximately the same range of colors as obtainable with printing inks and compares favorably as a display medium. The theoretical luminous efficiency of ZOD microimages for various subtractive primary and secondary colors are calculated and measured by RCA Laboratories, Zurich.

Luminous efficiency is defined as the ratio of the number of lumens transmitted to the aperture of the projection lens within the color band established by the ZOD microimages to the total number of lumens delivered by the source assembly to the ZOD storage plane. The measurement accounts for both the transmission of the storage medium, the diffraction efficiency, and the photopic response of the eye. (For the purpose of this experiment, a 2700°K source is assumed. This accounts for the apparent balance between the red and green efficiencies and the low efficiency of the blue.) Results of this experiment are given in Table IV below. Theoretical and measured values are seen to be in good agreement.

TABLE IV
ZERO ORDER DIFFRACTION EFFICIENCY FOR PURE COLORS

Color	Luminous Efficiency (%)	
	Theoretical	Experimental
Cyan	27.1	18.0
Magenta	21.0	18.3
Yellow	89.0	71.4
Red	20.0	13.9
Green	21.0	10.6
Blue	2.2	1.8
Black	2.2	0.9

Several slides were produced for evaluation using EK and FIH technology. Subject matter was varied and included reproduction of the same Aerial Navigation Chart. Color reproduction using FIH holograms is well documented⁽¹⁾ and is close to that obtainable using color television. Several subjects viewed each slide with the following results.

Aerial Navigation Chart (FIH) - Color saturation of navigation charts reproduced using FIH technology was excellent. However, small shifts in hue were perceptible in all areas of the spectrum. These small changes did not significantly effect the display's ability to convey useful information using color. Resolution of the chart was such that all printed areas were easily readable when viewed at 30 inches.

Aerial Navigation Chart (EK) - Color fidelity and saturation of the EK material was good. However, as was previously demonstrated, the resolution and thermal damage threshold of EK are low. In addition, color shifts in the EK dye material will occur as the result of readout (see Figure 4).

A variety of color bar charts were also produced using EK and FIH materials. The quality of these slides was found to be identical to the Aerial Navigation Charts mentioned above.

Experimental ZOD microimage slides of a variety of subjects were next evaluated. These slides were employed to qualitatively evaluate colorimetry, shading, and contrast of the display. With one exception, color separations and screening were performed by RCA, Zurich. Due to its excessive dimensions, the color separations and screenings of slide 7 (Aerial Map) were obtained from an outside vendor. The subjects selected are listed below.

(1) "HHSD Demonstration Model Development", Final Report, Dec. 1977, Prepared for Naval Air Development Center under Contract N62269-76-C-0390.

- Slide 1 Black resolution chart with cyan background.
- Slide 2 Black resolution chart with yellow background.
- Slide 3 Black resolution chart with magenta background.
- Slide 4 Portrait of girl with jewelry.
- Slide 5 Portrain of girl in outdoor environment with sunlight.
- Slide 6 Bowl of fruit with gold serving tray.
- Slide 7 Aerial Navigation Chart.

The projected images of these slides were evaluated by several observers with the following results:

Slides 1 through 3 were composed of a black resolution chart on a pure color background. Reproduction of a pure color required no screening. The chromaticity and saturation of the images was judged correct. The resolution of the image was found to be very high and not limited by the ZOD slide but by the projection lens of the display (see Figure 6).

Slides 4 and 5 required screening of the primary gratings in order to achieve the primary color mixture necessary for accurate flesh tone rendition. The flesh tones of slide 4, the girl with jewelry, were acceptable but not perfect. A slight pinkish cast was noted in the deeper flesh tones, probably attributable to incomplete correction in the screening process. The jewelry was impressively good -- a deep blue gem with highlighted facets in a platinum mount was sharply and accurately rendered. Slide 5, the sunlit girl, was of excellent quality. No defect in color hues or saturation was observed.

The bowl of fruit in slide 6 required rendition of almost the entire spectrum. The color and shading of the fruit were excellent. A gold metallic serving tray in the background came out in convincing detail and color. The screening of separations was done with great care.

Slide 7 - the color separations of the Aerial chart were produced and screened by a commercial graphic arts house. This vendor ordinarily produces sets of printing

plates (4 per set) for high grade magazine color work. Unfortunately, they had no previous experience with a 3 color process. The screened transparencies as received were not optimized for the ZOD primaries. In spite of this handicap, the map image was of fair color though saturation was not as high as desired. The magenta component appeared somewhat deficient. This gave rise to browns which looked greyish brown and whites which had a slightly greenish cast. Reds were weak and slightly brownish. Resolution was very good.

VII. CONCLUSION

Resolution, colorimetry, brightness, shading and contrast of ZOD microimages have been evaluated and compared with Focussed Image Holograms and Iktachrome slide material. The highlight brightness efficiency of ZOD microimages was found to be 10X that of FIH. Resolution of single layer ZOD microimages and FIH holograms are comparable (200 lp/mm). Colorimetry, shading and contrast of the ZOD microimages was judged good when subjectively evaluated. Some variation in the color quality of the ZOD slides was noted and is probably attributable to inaccurate gamma correction of the primary separations. This indicates greater care in the screening operation will be necessary to obtain consistently good results. Determining a suitable vendor or development of in-house capabilities where greater process control may be exercised will require further effort.

A conceptual design incorporating the brightness and efficiency advantages of ZOD microimages in an annotatable, multicolor display is briefly outlined in Appendix II.

VIII. RECOMMENDATION FOR CONTINUED EFFORT

RCA recommends a continuation of the current Zero Order Diffraction, ZOD, evaluation program as it applies to high brightness display system. The current program has shown the potential of ZOD for achieving the Navy requirement for a high brightness, combined Moving Map/Horizontal Situation display. In particular, the advantages of the ZOD approach are a high luminous efficiency and brightness, with resolution potentially approaching the FIH and superior to film systems. The approach also

offers a potentially simplified recording technique in comparison to FIH.

During the course of the current program, RCA has identified two possible approaches of implementation of the ZOD technology to the color map display application. These are:

- (1) Achieve high resolution color presentation by accurately registering the three ZOD layers of this color subtractive system.
- (2) Utilize a separated luminance and chrominance approach (similar in concept to the approach used in color broadcast television) to significantly reduce the registration requirements of the color ZOD.

The first approach was evaluated in comparing ZOD to FIH and film systems. The second approach is at present, conceptual.

RCA recommends continuation of the current study of ZOD technology as applied to the high brightness display application to determine which of the above two approaches is most suitable for development for the HSD application. In particular, areas which should be examined for both approaches are:

- (1) What are the color vs resolution requirements to achieve a satisfactory color map display, i.e., must the current color maps be reproduced retaining their current color fidelity and resolution and what latitude is available for alternate colors? For example: can current color contour lines be displayed as black or gray? This area directly effects the luminance/chrominance ZOD approach?
- (2) What is involved in obtaining the appropriate screened color (and luminance) source material for recording the ZOD maps? Can presently available (either within the Navy, RCA or industry) equipment supply the necessary source material or must modified or completely new facilities be developed and at what cost?
- (3) Is currently available sprocket and pin registration equipment utilized in the movie industry readily adapted to the requirements of ZOD recording and registration or must new equipment be developed and what is the cost to implement the required facility?

The above outlined tasks are the necessary first steps, as shown in the Development Flow Chart of Figure 11, to develop the demonstrated outstanding promise of ZOD to the Navy requirements for high brightness Moving Map cockpit displays.

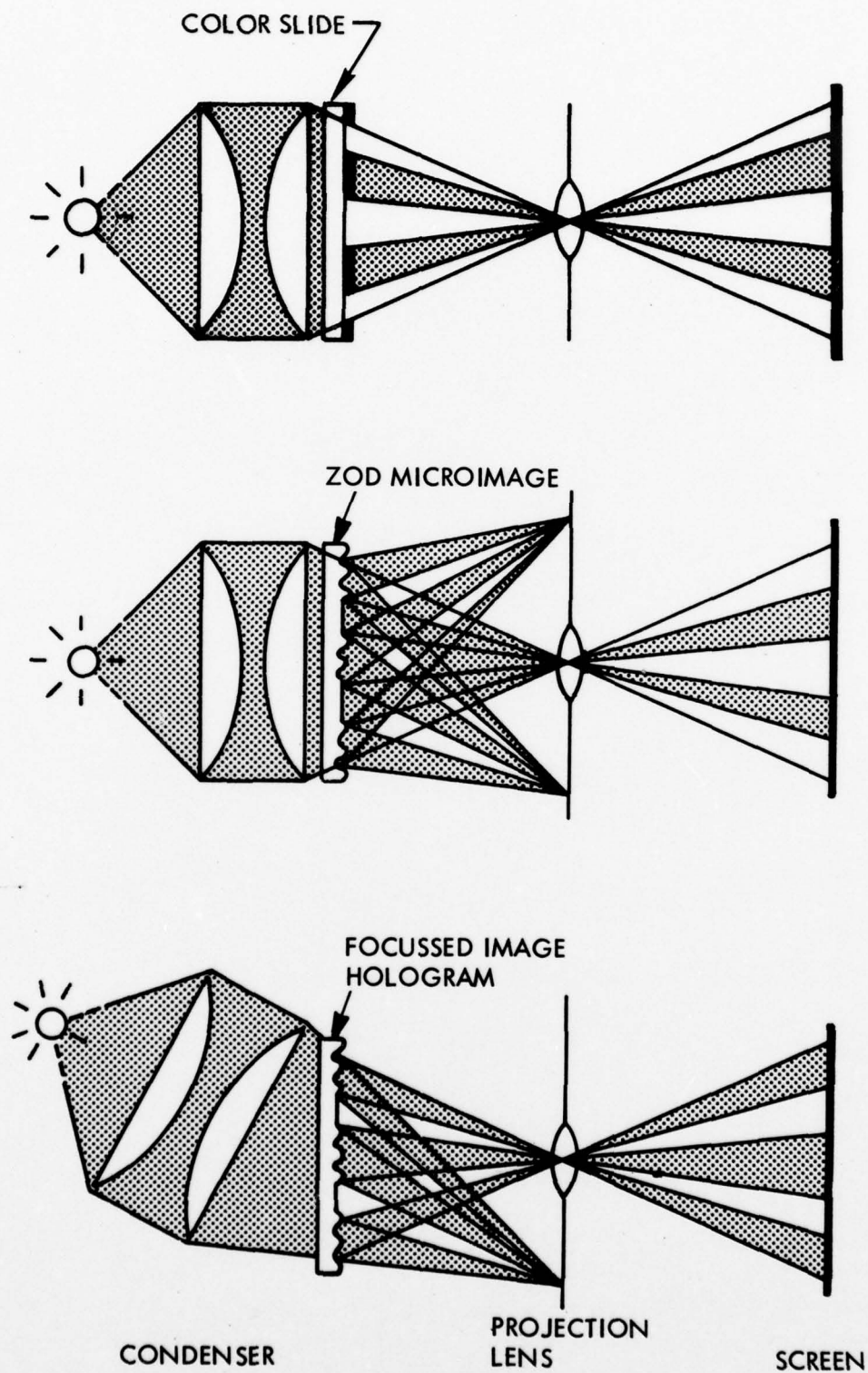


Figure 1. Projection Systems for Ektachrome, ZOD Microimage and Focussed Image Holograms

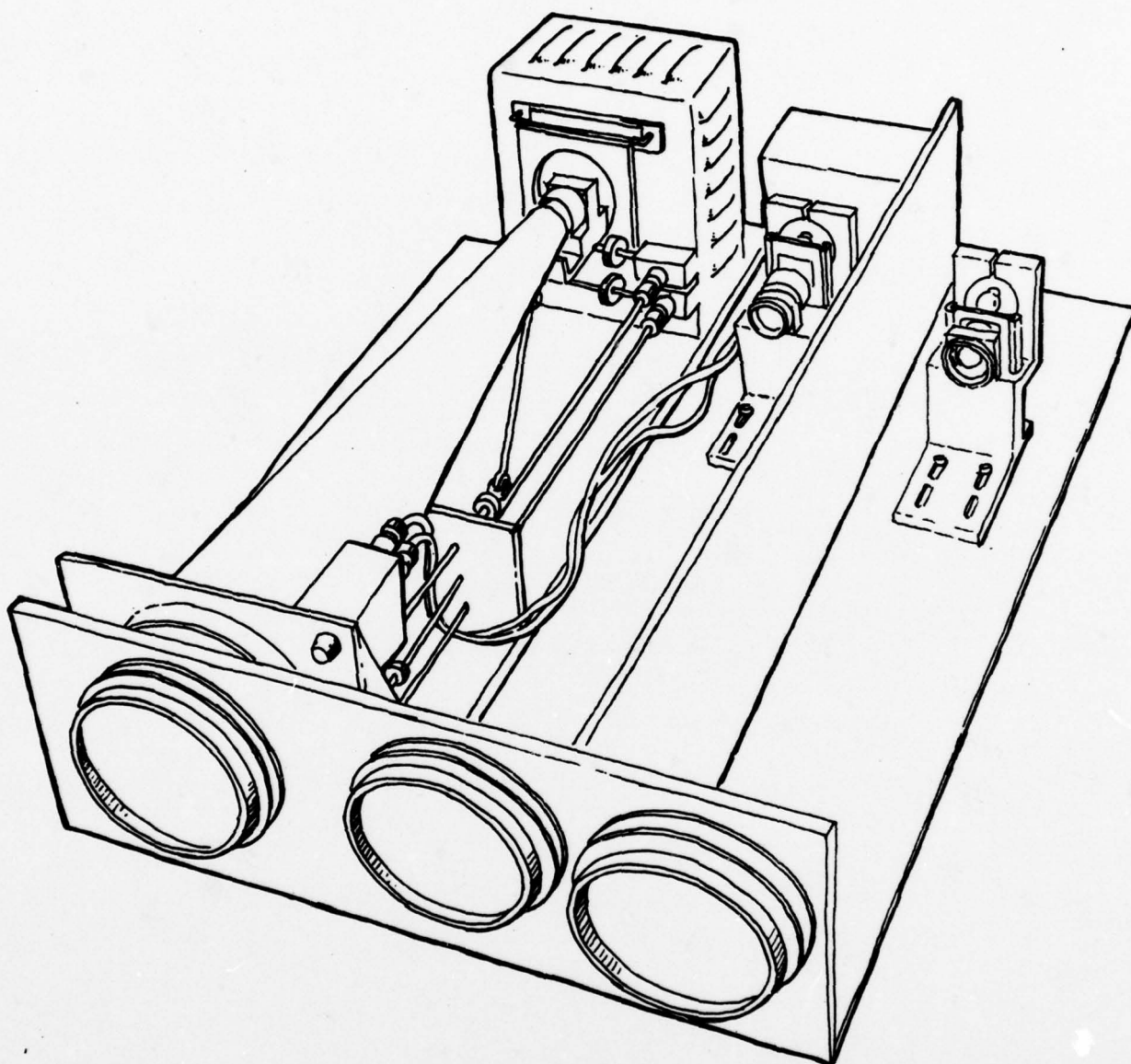


Figure 2. Image Evaluation Test Stand

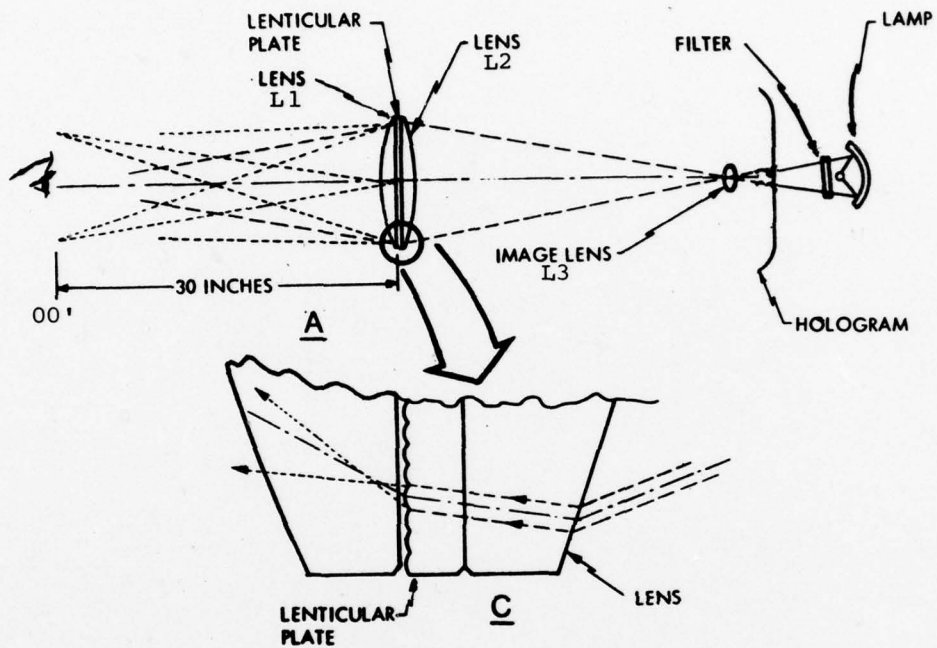


Figure 3. Directional Viewing Screen Configuration For ZOD and EK.

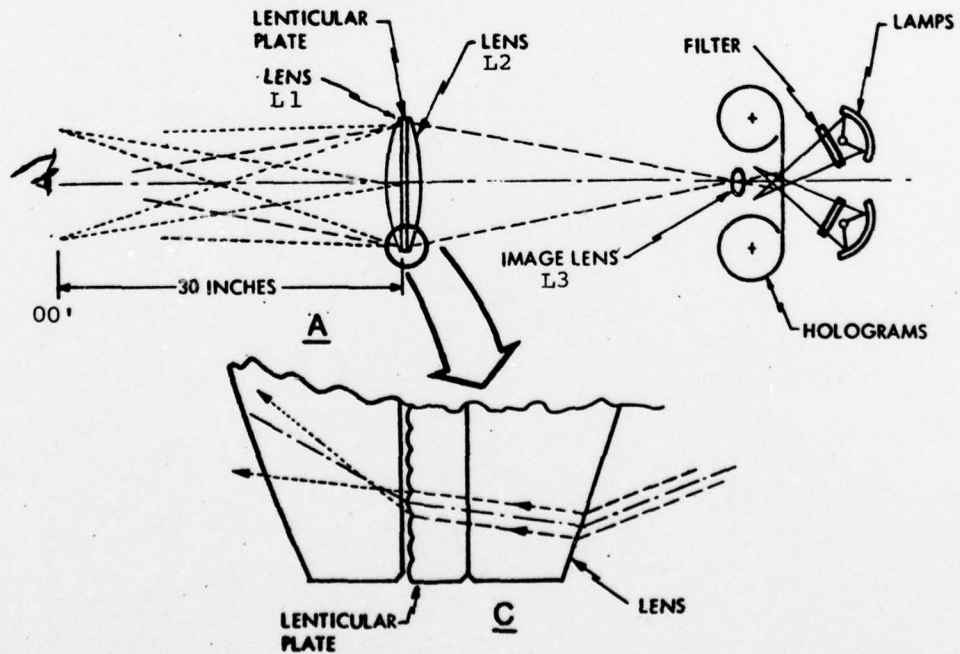


Figure 3b. Directional Viewing Screen Configuration For FIH.

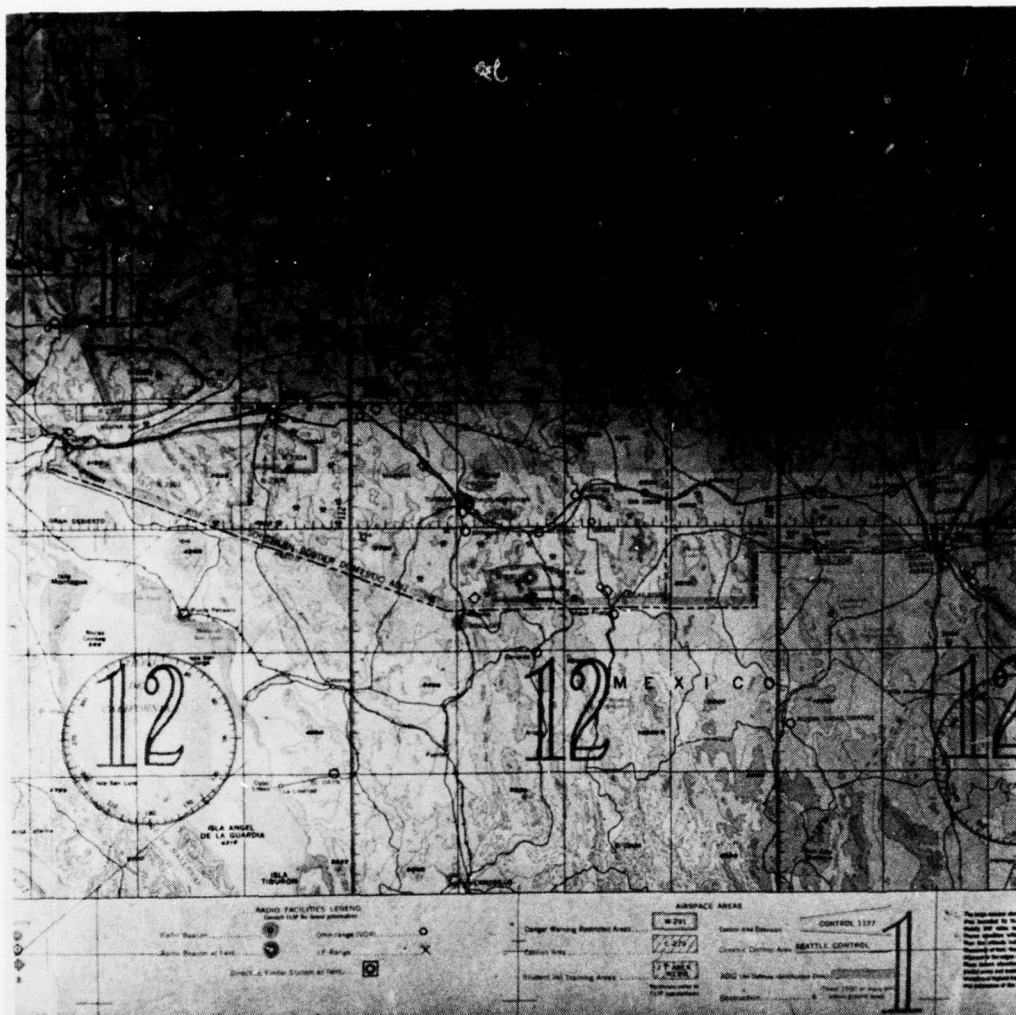


Figure 4. Bleaching of Ektachrome Slide

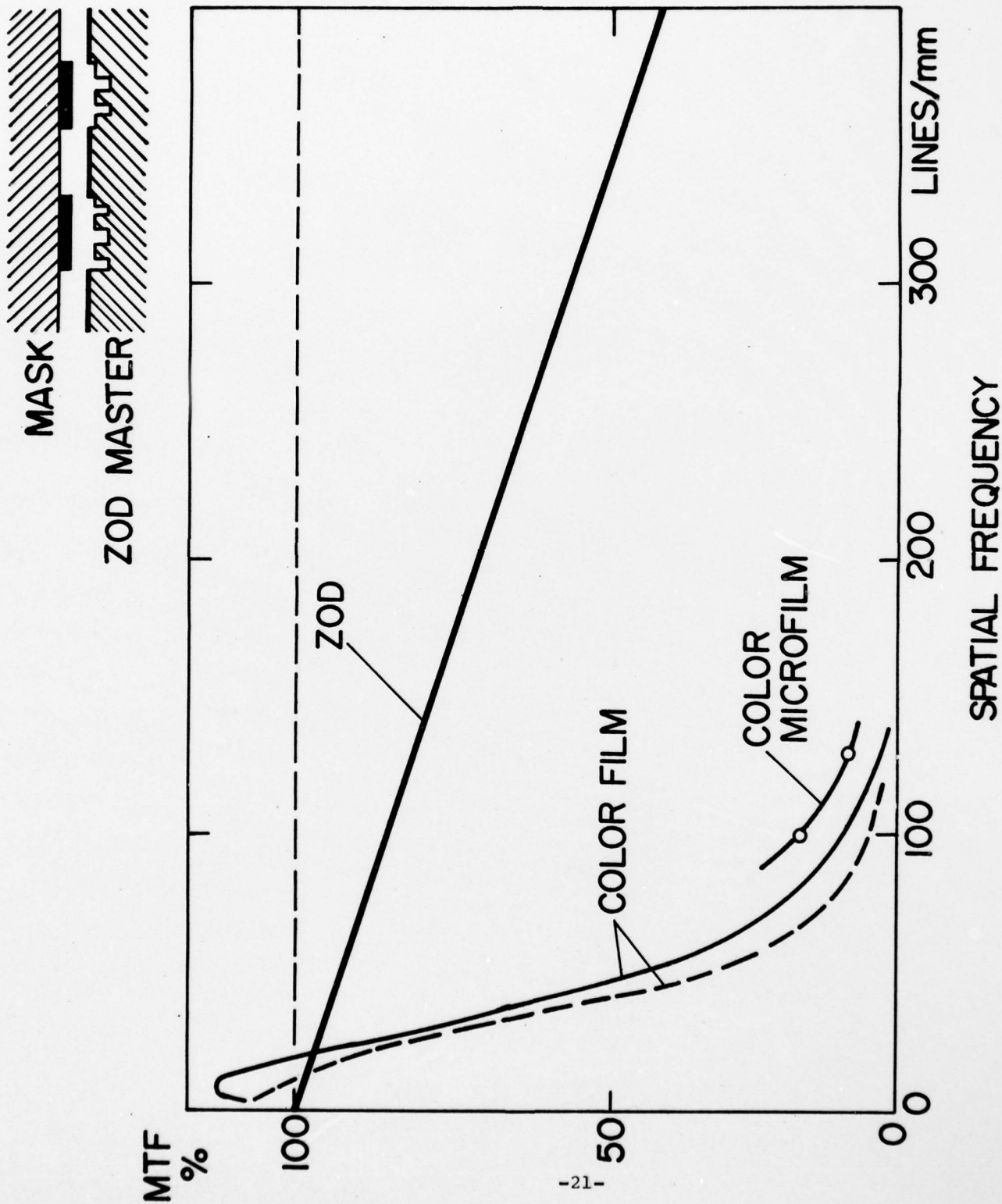


Figure 5. Estimated Modulated Transfer Function of Single Grating ZOD Microimages and Representative Color Films

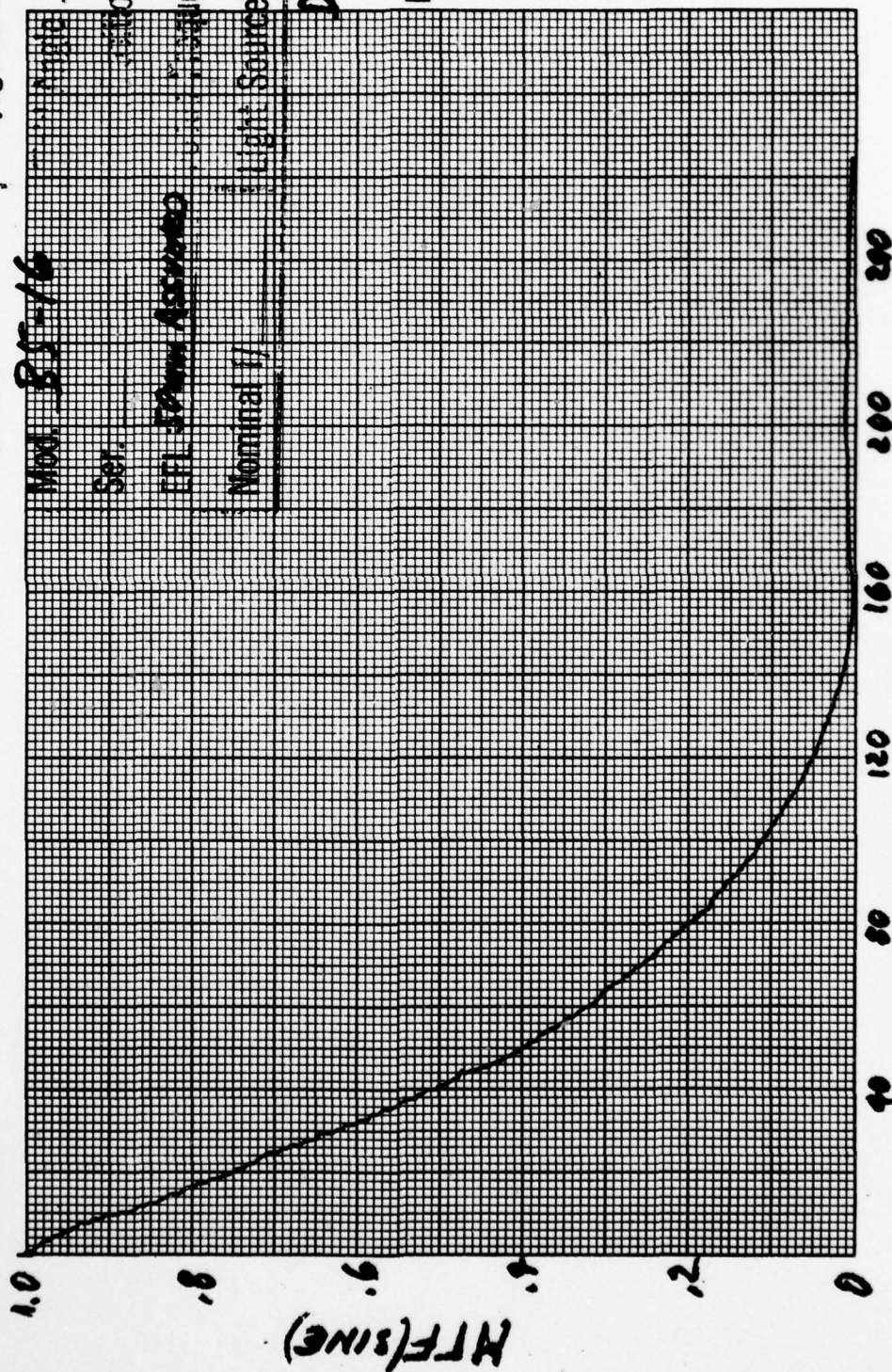
BEST focus @ 0°; 50c/mm

~30"

Mfg.	Conjugates	CLER
Mod. 85-16	Angle	0°
Ser.	Resolution	4000 LIT
EFL 50mm Assumed	Frequency	50
Nominal f/	Light Source	3300 ft.

DET. 520

DEC 3 0 1977



Cycles/mm

Figure 6. Modulation Transfer Function of Projection Lens Employed in ZOD Display

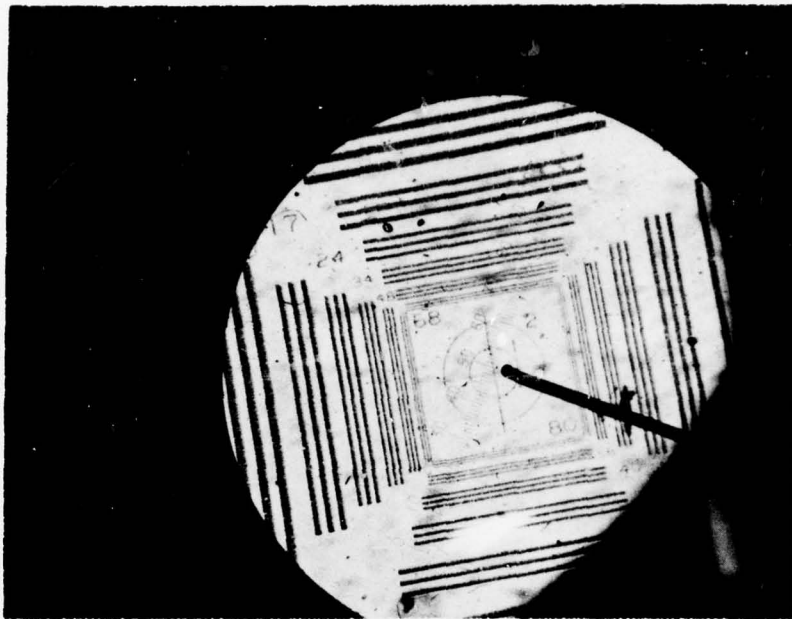


Figure 7. FIH Resolution Chart Showing Resolution in
Excess of 150 lp/mm magnification M=63

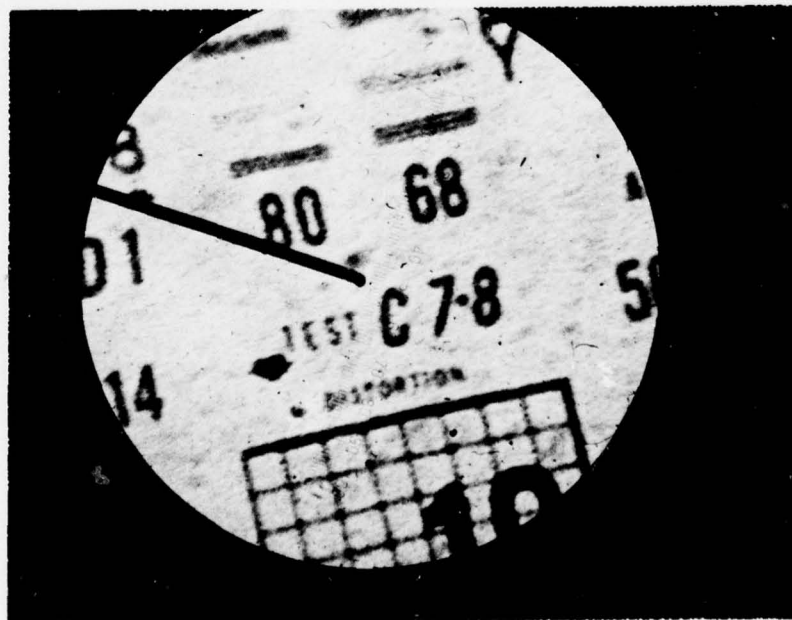


Figure 8. Ektachrome Resolution Chart Showing Resolution of
71 lp/mm magnification M=56

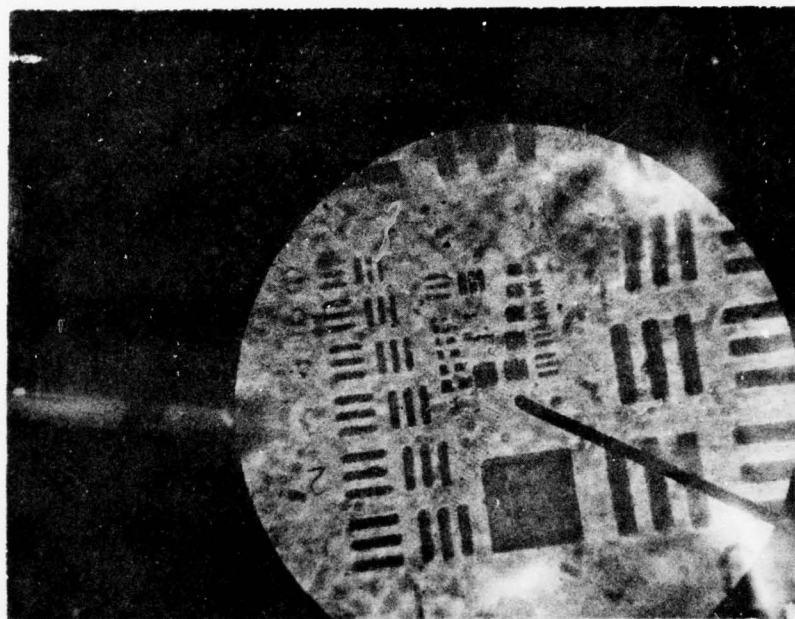


Figure 9. ZOD Resolution Chart Showing Resolution
of 225 lp/mm Magnification $M = 221$

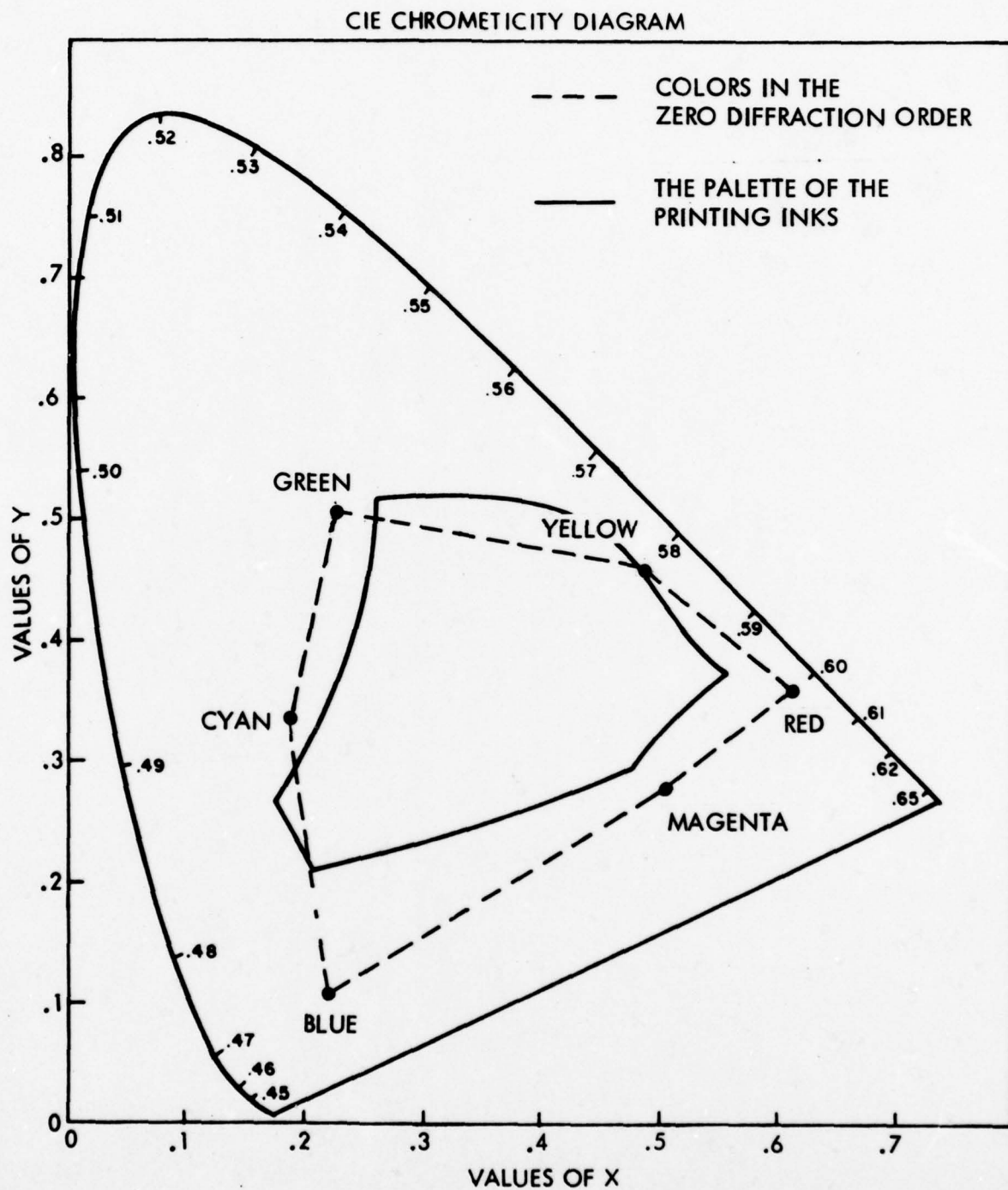


Figure 10. Range of Color Reproducibility Employing Standard Printing Inks, ZOD Microimages and FIH Holograms

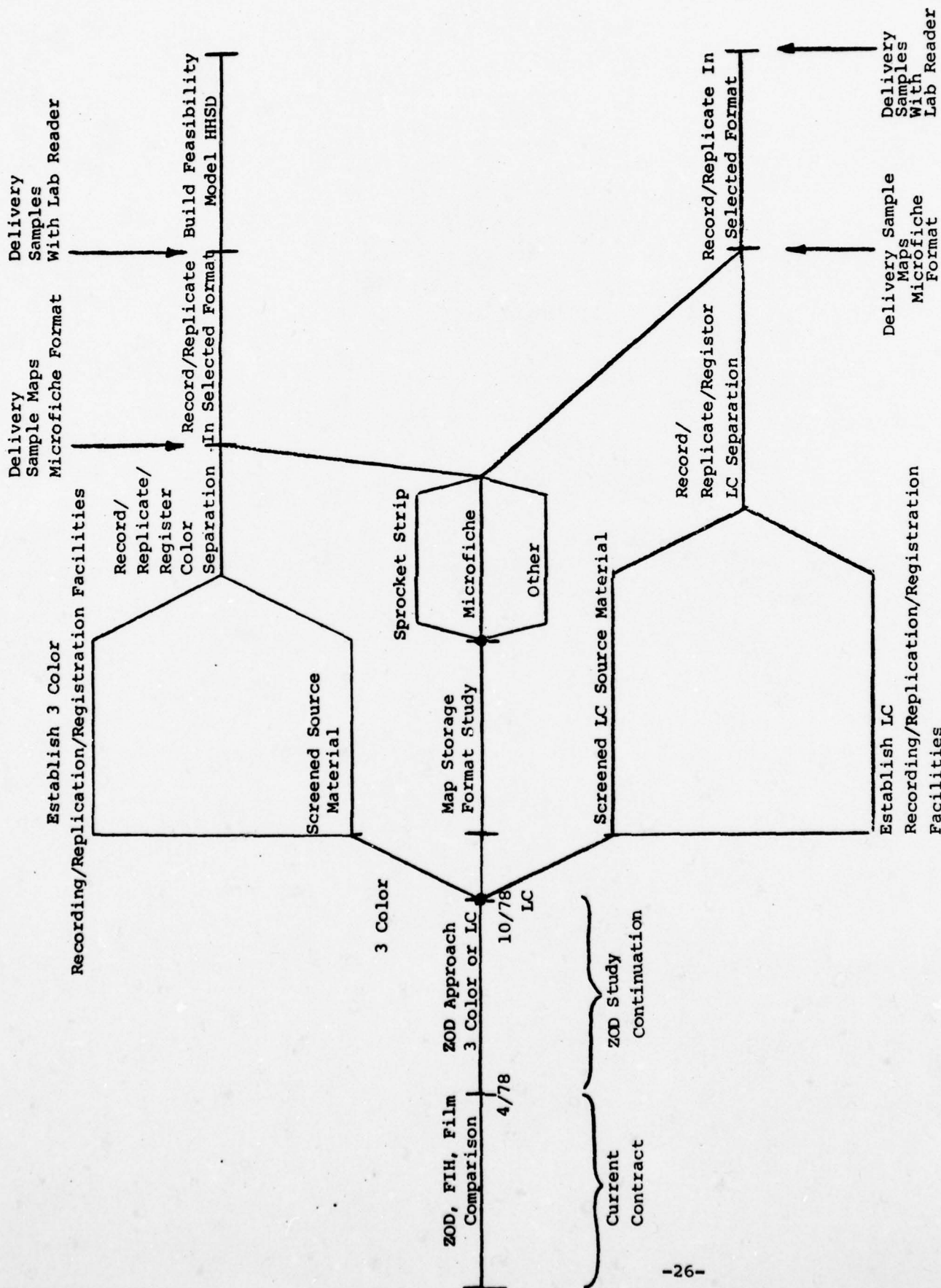


Figure 11. ZOD Technology Development

APPENDIX I
ZOD MICROIMAGE TECHNOLOGY

1. INTRODUCTION

Zero Order Diffraction (ZOD) microimagery is a promising new technique allowing information storage and display, recently developed by RCA's Research Center in Zurich, Switzerland. The attractive characteristics of ZOD systems stem from these two facts:

ZOD microimages have very high optical efficiency, and
absorb a negligible amount of projected light energy.

Section 2 of this Appendix compares current technologies used to obtain color displays and indicates their basic differences. Section 3 is a detailed description of how a ZOD hologram creates a color image, the parameters that must be satisfied to ensure compatibility with standard projection optics, the manufacturing processes, and an analysis of the expected brightness of ZOD microimages.

2. COMPARISON OF TECHNICAL APPROACHES

Figure 1-1 illustrates the basic differences between conventional color, ZOD and Focussed Image Hologram (FIH) projectors. In all cases, the individual picture elements recorded on the slides (or film) selectively reduce the amount of light that reaches the screen.

The main difference between a ZOD slide and a conventional color slide is the method by which the projected light is modulated the proper amount for each picture element. In a color slide, picture information is contained in several color absorptive layers. The individual layers absorb unwanted light at each picture element location on the slide. In a ZOD slide, picture information is contained in surface corrugations which diffract the unwanted light out of the optical system.

Thus, a very significant difference between ZOD and conventional color slides is the fact that a color slide absorbs unwanted light, converting it to heat in the slide itself, whereas a ZOD slide diffracts unwanted light out of the optical system where it is absorbed in the walls of the projector. Consequently, a ZOD slide can accept a high level of incident illumination without fading or suffering from other forms of degradation associated with heat absorption.

A basic difference between ZOD and FIH slides (also illustrated in Figure 1) is that the ZOD slide diffracts unwanted light out of the optical system. Although this may appear to be a trivial difference, the consequences have beneficial effects on image brightness, player complexity and stability requirements of recording equipment.

The advantages and disadvantages of the ZOD technology, as confirmed during earlier discussions of this report, are summarized below:

- Brightness - ZOD images can be displayed with 100 percent transmission efficiency. In contrast, the efficiency of a color slide is only about 50 percent.
- Compatibility - Images from ZOD holograms can be projected by a conventional, unmodified slide projector.
- Player Simplicity - A ZOD player will require only one projector lamp. Also, ZOD images can be rotated by simply rotating the hologram itself.
- Recorder Simplicity - A laser is not needed to record ZOD holograms.
- Low Cost - ZOD holograms can be embossed on the surface of low cost plastic film.
- Archival - Embossed holograms provide excellent color stability and do not suffer from fading due to heat or aging.

ZOD holograms have these two disadvantages:

- Registration - The three replicas (which form each ZOD hologram) must be accurately registered in a laminated structure.

- Screening - Gray scale and color require the use of screened object transparencies.

3. THE ZOD TECHNOLOGY

3.1 Colorimetry

As previously stated, a ZOD microimage diffracts unwanted light out of the optical system. In this regard, a ZOD microimage functions similar to a subtractive color filter - it eliminates (subtracts) unwanted color, allowing only the desired colors to reach the projection screen.

Square wave phase gratings (see Figure 1-2) are used for producing color in the zero diffraction order. As shown in Attachment A to this appendix, a wide range of different spectral transmission curves can be realized by varying the depth D of the square wave grating. In particular, for a material with refractive index $n = 1.5$, the three depths $D = 1.22, 1.56$ and $1.87 \mu\text{m}$ lead to a wavelength dependence of the zero diffraction order over the visible range as shown in Figure 1-3. The transmittance minima for these three particular gratings occur at the three primary colors, red, green and blue, respectively. With incident white light, the colors obtained in the zero-order direction are, therefore, cyan (minus red), magenta (minus green) and yellow (minus blue). These are the three colors used in subtractive color systems such as color photography and color printing.

By superimposing these three gratings in a tripack structure, and by applying screening techniques such as those used in printing halftones, a full color picture can be reproduced. The optimum choice of individual grating depths is determined by the desired overall color range. A reasonable set of depths is obtained by fitting the subtractive primary colors to existing standards for printing dyes. Fig. 1-4 shows the ZOD color range obtained by this approach. It matches the range of colors occurring in nature and is close to the range covered by the subtractive color photographic processes. ZOD colors within the area shown are obtained by dividing each picture element into two regions, one clear (corresponding to white) and the other carrying a grating structure (corresponding to a primary color), in a manner analogous to conventional screening techniques. The ratios

of clear to grating area for the three gratings determine the three color parameters, hue, saturation and brightness. Black is obtained when all three gratings are fully present. By this means, a total luminous range of 50:1, (see Table IV of text) can be reproduced with good gray scale.

3.2 Compatibility

To assure that ZOD slides are compatible with conventional projectors, the grating periodicity must be small enough to make sure that the projection lens does not intercept light diffracted into the higher orders. This is accomplished for a projector lens of given f number when

$$\frac{\lambda}{d} = 1/f\text{-number}$$

For virtually all projectors in use today (f-number ≥ 2.8), a grating constant $d = 1.4\mu\text{m}$ (or smaller) is sufficient to guarantee full compatibility. Such grating constants are readily obtained for the square wave grating used for ZOD holograms.

3.3 Manufacturing Process

The manufacturing process involves the following five basic steps. A brief description of each step is given below.

- (1) Fabrication of master blanks
- (2) Fabricating of recording material
- (3) Image recording
- (4) Fabrication of metal masters
- (5) Replication

Master Blanks - As shown in Figure 1-5, an original metal grating master is fabricated by contact printing a grating pattern on a layer of photoresist. The photoresist must be carefully deposited so that its thickness matches the desired depth of the phase grating. After development, the surface is plated with Ni.

The Ni layer is then separated and serves as the original grating master from which the recording substrate material is fabricated.

Recording Material - The original metal blank described above is used to fabricate replica blanks. This is done by embossing plastic replicas and subsequently plating them and then stripping the plated layers to produce metal replicas which serve as the recording substrate material. These substrates are then coated with photo-resist to produce the recording material (see Figure 1-6(a)).

Image Recording - Image recording (see Figure 1-6(a)) involves exposing the recording material either by contact printing or by projecting an image from a screened object transparency onto the photoresist-coated surface.

Metal Master - After development of the resist (see Figure 1-6(b)), the grating structure is destroyed by Ni electroplating (see Figure 1-6(c)) in those areas that have been exposed (white areas). The remaining resist is removed (see Figure 1-6(d)) and the metal master is then ready for embossing. For full-color pictures, the complete procedure is repeated three times using three different metal master blanks in accordance with the color separation transparency used. (For black-and-white pictures, a single metal master with a sinusoidal profile is adequate.)

Replication - Many copies can be made by using the metal master to emboss the ZOD patterns on clear thermoplastic sheet material such as polyvinyl chloride (PVC), cellulose acetate, polycarbonate, etc.⁽¹⁾ With electrically heated masters, embossing times are very short; e.g., less than 0.1 second for a 10 x 14 mm microfiche slide.

3.4 Brightness

A lower bound on the potential brightness advantage of ZOD microimage relative to FI holograms can be determined by assuming that the image is an all-white field,

(1) W. J. Hannan et al., "Holotape: A Low Cost Prerecorded Television System Using Holographic Storage, "Journal of the SMPTE, November 1973.

and the FI hologram is recorded so that brightness is maximized (i.e., neglecting the brightness which must be sacrificed in practice to achieve satisfactory colorimetry). The transmission efficiency of a ZOD hologram of an all-white field is 100 percent, since, for this case, a ZOD hologram does not diffract any light beyond the collection range of the projection lens. The transmission efficiency of a FI microimage of the same all-white field is equal to the percent of incident light flux that is diffracted into the first order beam. Accordingly, from Equation 14 of Attachment B, the efficiency of a FI hologram is

$$\eta = [J_1(\beta)]^2$$

As shown in Figure 1-7, the maximum value of $J_1(\beta)$ is 0.581, corresponding to $\beta_{\max} = 1.839$ radians; therefore, maximum efficiency is $\eta_{\max} = (0.581)^2 = 0.34$ or 34 percent. The use of a projector, employing six projection lamps that utilize both 1st order beams, allows the theoretical efficiency to be as high as 68 percent. However, as pointed out by Firester, ⁽²⁾ efficiency of a FI hologram must be sacrificed to realize satisfactory colorimetry. A practical bound on efficiency is about 26 percent for double beam readout. Therefore, a realistic estimate of the brightness advantage of ZOD microimages is about 4:1. Moreover, taking into account a 3:1 light loss in a FI projector caused by the red, blue and green filters (required in the primary readout beams), the estimated brightness advantage of ZOD microimages becomes higher by a factor of about 12:1 or for the same image brightness, the use of ZOD microimages allows a 12:1 reduction of projector lamp power.

⁽²⁾ A. H. Firester, "Efficiency and Colorimetry of Color Encoded Focused Image Holograms," RCA Report ZRRL-73-TR-010, June 1973.

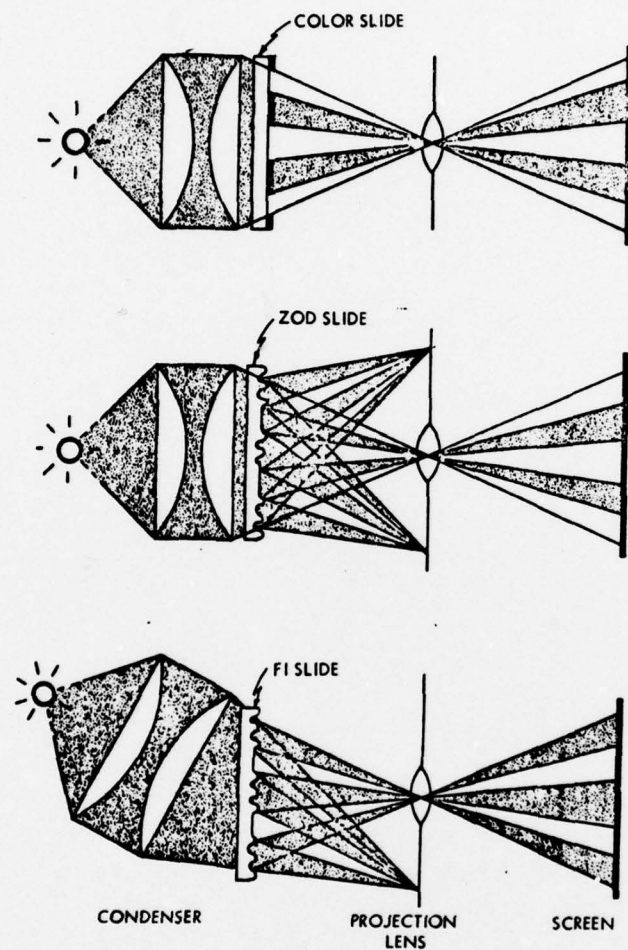


Figure 1-1. Comparison of Conventional Color, ZOD and FI Projectors

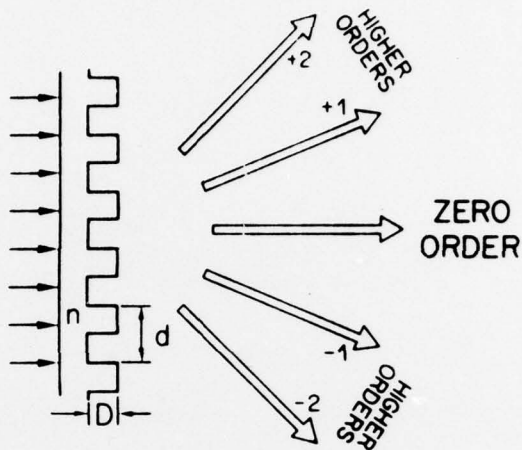


Figure 1-2. Squarewave Relief Phase-Grating
For Color ZOD Microfiche

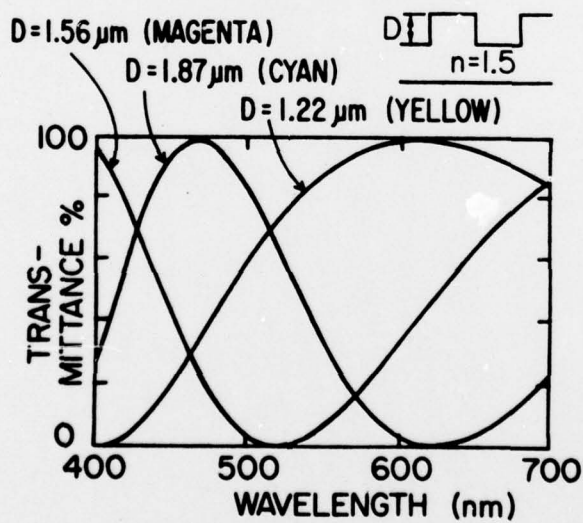


Figure 1-3. Zero Order Transmittance in the
Visible for Squarewave Gratings

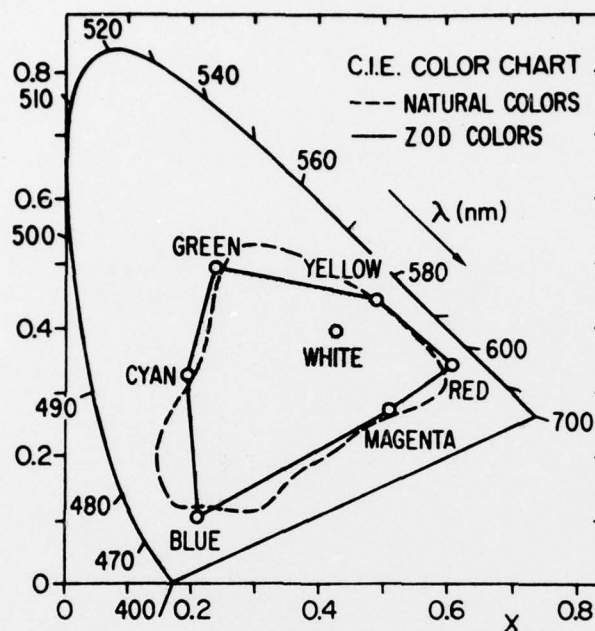


Figure 1-4. Color Range of ZOD Holograms

PRODUCTION OF ORIGINAL GRATING

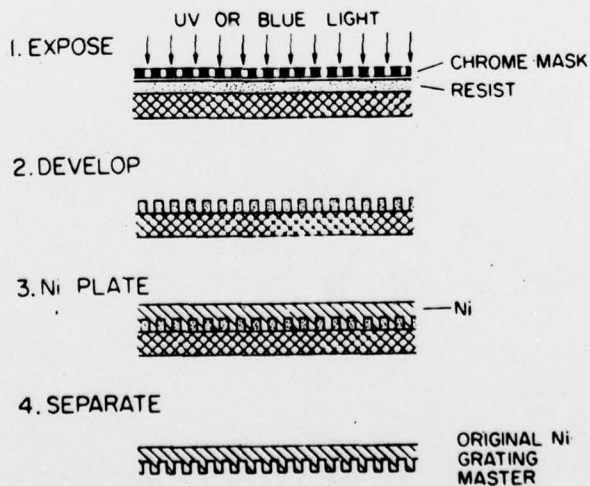


Figure 1-5. Production of Original Grating

IMAGE RECORDING ON MASTER BLANK

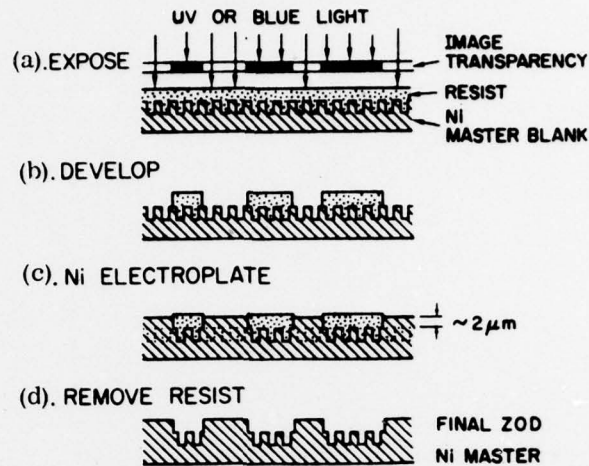


Figure 1-6. Image Recording on Replica of Master Blank

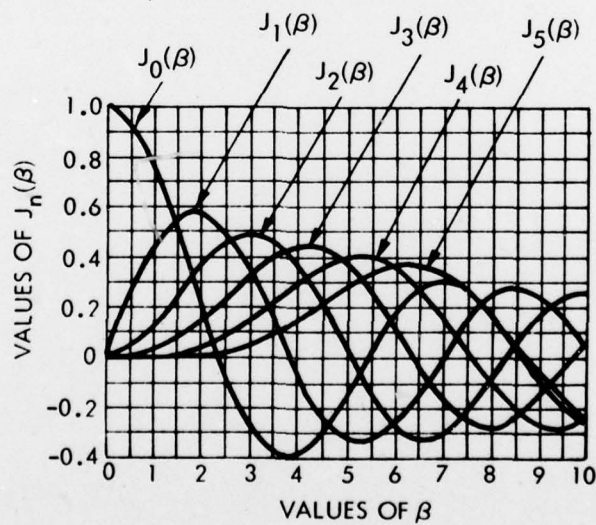


Figure 1-7. Bessell Function Values

APPENDIX I

ATTACHMENT A

ZERO ORDER TRANSMITTANCE OF A SQUARE WAVE PHASE GRATING

To understand the picture encoding method used for ZOD holograms, it is useful to recall the optical properties of a square-wave relief phase-grating such as illustrated in Figure A-1. When placed in the path of a parallel beam of white light, the grating has no effect on those spectral components whose wavelength is a submultiple of the optical path difference between the two surface levels, i.e., for

$$\lambda = \frac{D}{M} (n - 1)$$

where:

D = square-wave profile depth

n = refractive index

λ = wavelength

M = 1, 2, 3, . . .

At all other wavelengths the grating permits only a reduced amount of light to continue in its original direction, while it diffracts the remainder toward a number of new, well defined directions whose angles satisfy the relation

$$\sin \alpha = \frac{N\lambda}{d}$$

where

d = grating period

N = $\pm 1, \pm 2, \pm 3, \dots$ are the diffraction orders.

TRANS- MITTANCE

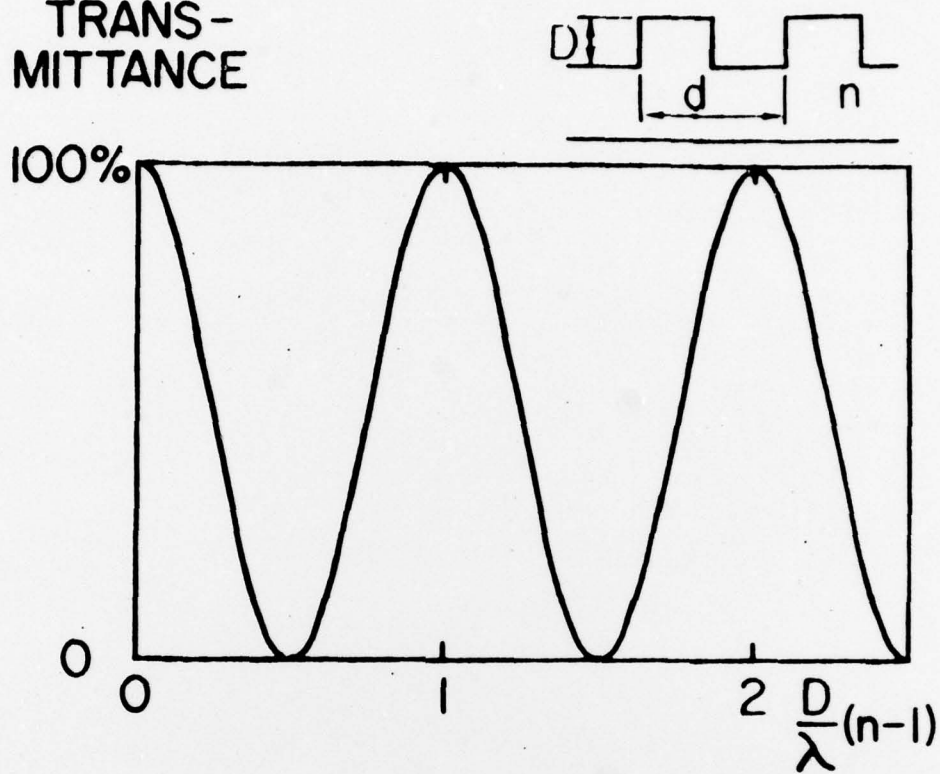


Figure A-1. Zero-Order Transmittance for Squarewave Phase-Gratings

As a result, the light intensity transmitted in the original, undisturbed direction (the so-called "zero-order") has the wavelength dependence shown in Figure A-1. It reaches zero transmittance at wavelengths given by

$$\frac{D}{\lambda} (n - 1) = M - \frac{1}{2}$$

In general, the zero-order transmittance is given by the relation

$$I(\lambda) = \cos^2 \left(\frac{\pi D}{\lambda} (n - 1) \right)$$

APPENDIX I

ATTACHMENT B

EFFICIENCY OF PHASE HOLOGRAMS

The fundamental properties of phase holograms can be derived from the simple recording geometry shown in Figure B-1. If both the object and reference beams are plane waves, the complex field amplitude of the light incident on the recording medium is

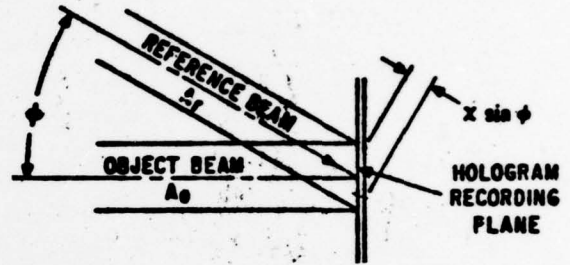


Figure B-1. Recording Geometry

$$U = A_o + A_r \exp \left[i\omega_x X \right] \quad (1)$$

where $\omega_x = 2\pi \frac{\sin \phi}{\lambda}$ is the spatial frequency of the hologram fringes and A_o and A_r are the complex field amplitudes of the object and reference beams, respectively. It follows that the intensity is

$$|U|^2 = A_o A_o^* + A_r^2 + A_o^* A_r \exp \left[i\omega_x X \right] + A_o A_r^* \exp \left[-i\omega_x X \right] \quad (2)$$

In this simple example $A_o A_o^* = A_o^2$ because the object beam is a plane wave; therefore Equation (2) can be expressed as

$$|U|^2 = A_o^2 + A_r^2 + 2A_o A_r \cos \omega_x X \quad (3)$$

Note, however, that this represents a very special case. In the case of a complicated object, $A_o A_o^*$ is neither real nor constant and it has frequency components extending to twice the frequency spectrum of the object alone.

Now, with regard to surface relief holograms, assume a recording medium which undergoes a change in thickness which is directly proportional to exposure:

$$\Delta l = g |U|^2 T \quad (4)$$

$$= g \left[A_o^2 + A_r^2 + 2A_r A_o \cos \omega_x X \right] T \quad (5)$$

where g is the (change in thickness)/(exposure) constant of the material and T is exposure time. Accordingly, hologram transmittance is

$$T_h = \exp \left[i (n-1) k \Delta l \cos \varphi \right] \quad (6)$$

where n is the refractive index of the recording (or replicating) material and $k = 2\pi/\lambda$.

When read out by a reference beam $A_i \exp [i \omega_x X]$, as illustrated in Figure B-2, the complex field amplitude of the light diffracted by the hologram is

$$S = A'_r \exp i \omega_x X \cdot \exp \left[i (n-1) k \Delta l \cos \varphi \right] \quad (7)$$

Substituting (5) in (7) we get

$$S(x) = A'_r \exp [i\Theta] \cdot \exp [i \omega_x X] \cdot \exp \left[i 2 (n-1) k g T A_o A_r \cos \omega_x X \cos \varphi \right] \quad (8)$$

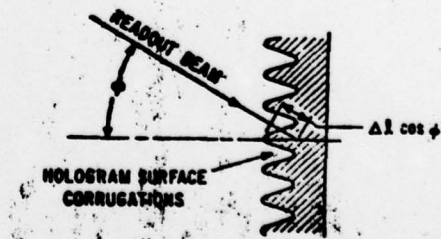


Figure B-2. Readout Geometry

where $\Theta = kgT (n-1) (A_o^2 + A_r^2) \cos \varphi$, Equation (8) can be expanded as a Fourier series:

$$S(x) = \sum_{n=-\infty}^{\infty} C_m \exp [imX\omega_x] \quad (9)$$

where

$$C_m = \frac{\omega_x}{2\pi} \int_{-\pi/\omega_x}^{\pi/\omega_x} S(x) \exp [-imX\omega_x] dX \quad (10)$$

$$= \frac{\omega_x}{2\pi} A'_r \exp [i\Theta] \int_{-\pi/\omega_x}^{\pi/\omega_x} \exp \left\{ -i \left[(m-1) \omega_x X - 2 (n-1) kgT A_o A_r \cos \omega_x X \cos \varphi \right] \right\} dX \quad (11)$$

To get this expression into a more recognizable form, let $y = \omega_x X$; $\beta = 2 (n-1) kgT A_o A_r \cos \varphi$, and $A'_r e^{i\Theta} = D$; then

$$C_m = \frac{D}{2\pi} \int_{-\pi}^{\pi} \exp \left\{ -i \left[(m-1) y - \beta \cos y \right] \right\} dy. \quad (12)$$

Recognizing that

$$J_m(\beta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \exp \left\{ i \left[my + \beta \cos y \right] \right\} dy, \quad (13)$$

where $J_m(\beta)$ is a Bessel function of the first kind and order m , allows the Fourier components to be expressed as

$$C_m = DJ_{(1-m)}(\beta) \quad (14)$$

Thus, the complex field amplitude of the light diffracted by this particular hologram, which is actually a simple phase grating, is given by

$$S(x) = D \sum_{m=-\infty}^{\infty} J_{(1-m)}(\beta) \exp \left[im \omega_x X \right] \quad (15)$$

indicating that the complex field amplitude of the reconstructed object is proportional to $J_1(\beta)$, as shown in Figure B-3.

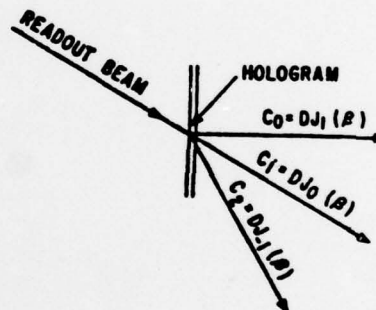


Figure B-3. Reconstructed Beams

APPENDIX II

CONCEPTUAL DESIGN OF A ZOD FICHE DISPLAY

ZOD technology offers two advantages over FIH: (1) The size of the ZOD player can be smaller since only one lamp is needed. (A similar FIH display would require 6 lamp assemblies.) (2) The input power required to achieve a given brightness level in a ZOD display is less than that required for FIH or conventional color film displays.

A conceptual design utilizing these advantages is sketched in Figure 2-1. It is basically a microfiche format employing a cylindrical drum for ease of playback and higher storage density.

The recorded maps are assembled on a microfiche mosaic and wrapped around a precision perforated drum (Figure 2-2). To load a Fiche the projection screen is pulled out on extendable tracks. In this position easy access to the drum allows rapid and accurate film placement.

The external dimensions of the device are 7 x 7 x 21.5 inches. The lamp-reflector-socket assembly is located at 45° to the horizontal axis so as to utilize corner space. In the event of lamp failure, two spare assemblies can be automatically brought into use without overtaxing space in the display.

The fiche covers most of the 100 square inch drum area. The tentative drum specifications are:

Diameter	6.2 inches
Length	7 inches
Perforations	15mm x 15mm
Maps	300 (1500 x 1000 nmi)

A cylindrical fiche format with discrete maps leads to a positioning mechanism which is smaller, simpler and lighter than a comparable tape drive mechanism which does rapid retrieval, and slow motion tracking in X and Y. An escapement

mechanism similar in function to that used on typewriter carriages is used to step the drum from frame to frame. Such a mechanism would consist of a double acting solenoid and detent latch. Fine adjustment for tracking is accomplished by a small stepping motor having an integral differential ball reducer of zero backlash. The range of the tracking action is slightly greater than the frame to frame distance.

A further simplification is now possible as a result of fixing the fiche to the drum, viz the precision metal drum allows the frames to be accessed by row and column tracks on the drum. This allows X and Y position information contained in the holograms of a tape format player to be dispensed with since frame position tracks would be a part of the drum.

A very significant contribution to smaller package size is the use of a reflective liquid crystal light valve in the annotation plane indicated in Figure 2-1. While suggested here, the use of a light valve of this type must be thoroughly explored with regard to gray scale, resolution, brightness, dynamic range, size and reliability to make certain it will meet the vertical situation display goals.

The approach presented above offers the advantage of reduced size and complexity at the expense of reduced ground area coverage - but since the fiche is easy to load, this may not be too high a price to pay.

This conceptual design is offered as one of many possible packages. A detailed study would be necessary to determine the overall advantage of the fiche or tape formats.

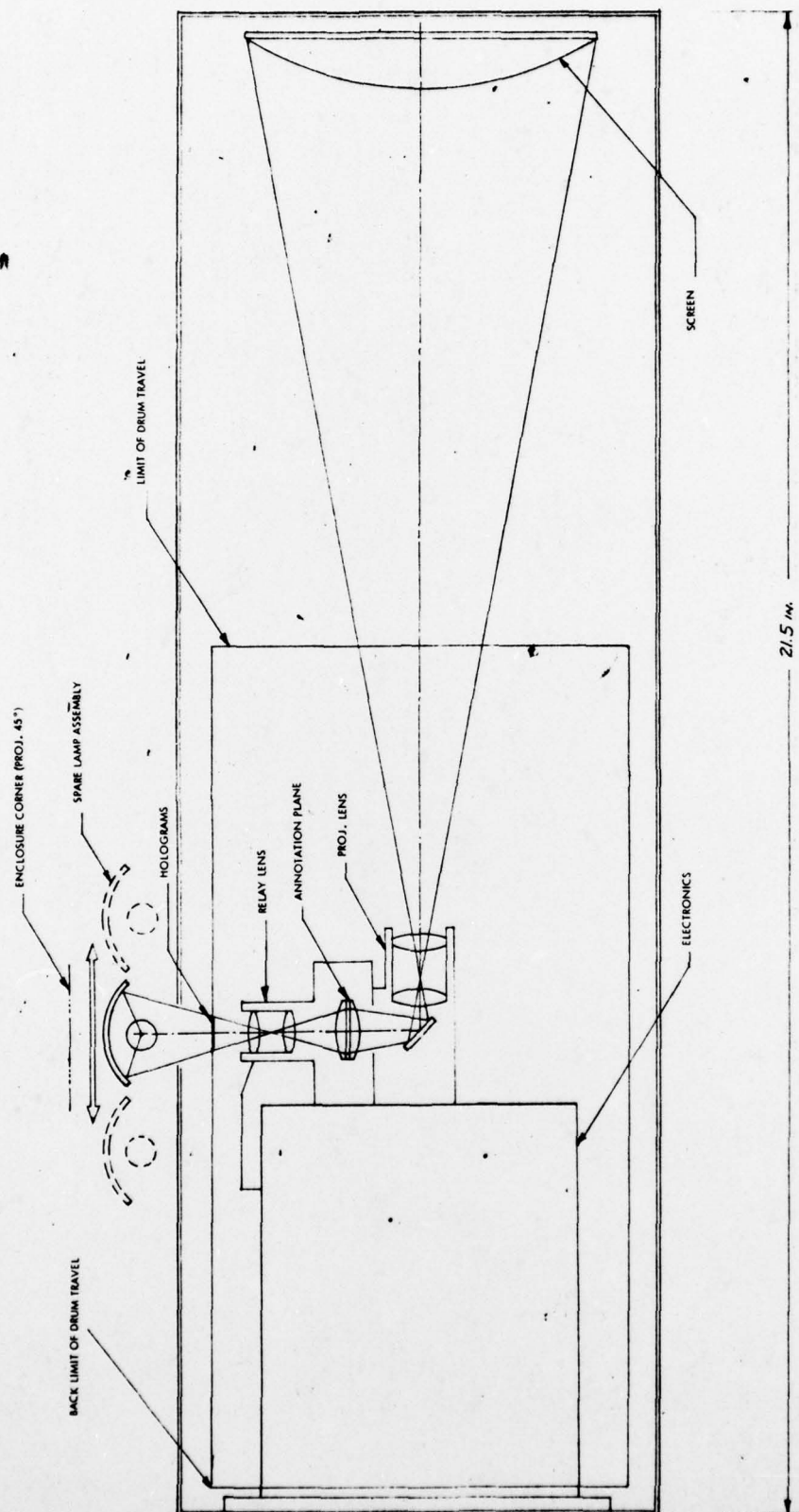


Figure 2-1 (a) Side View of ZOD reader using size reduction techniques to achieve a 7 in x 7 in x 21.5 in package.

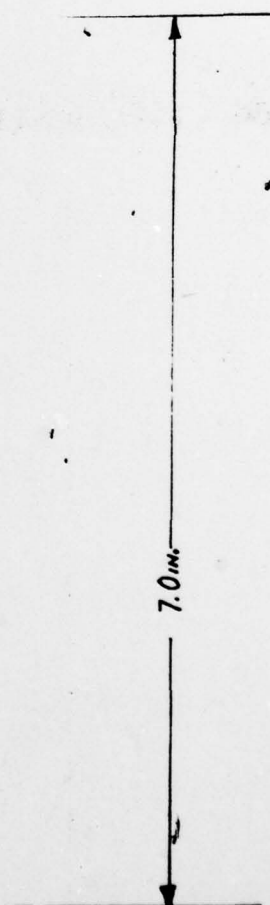
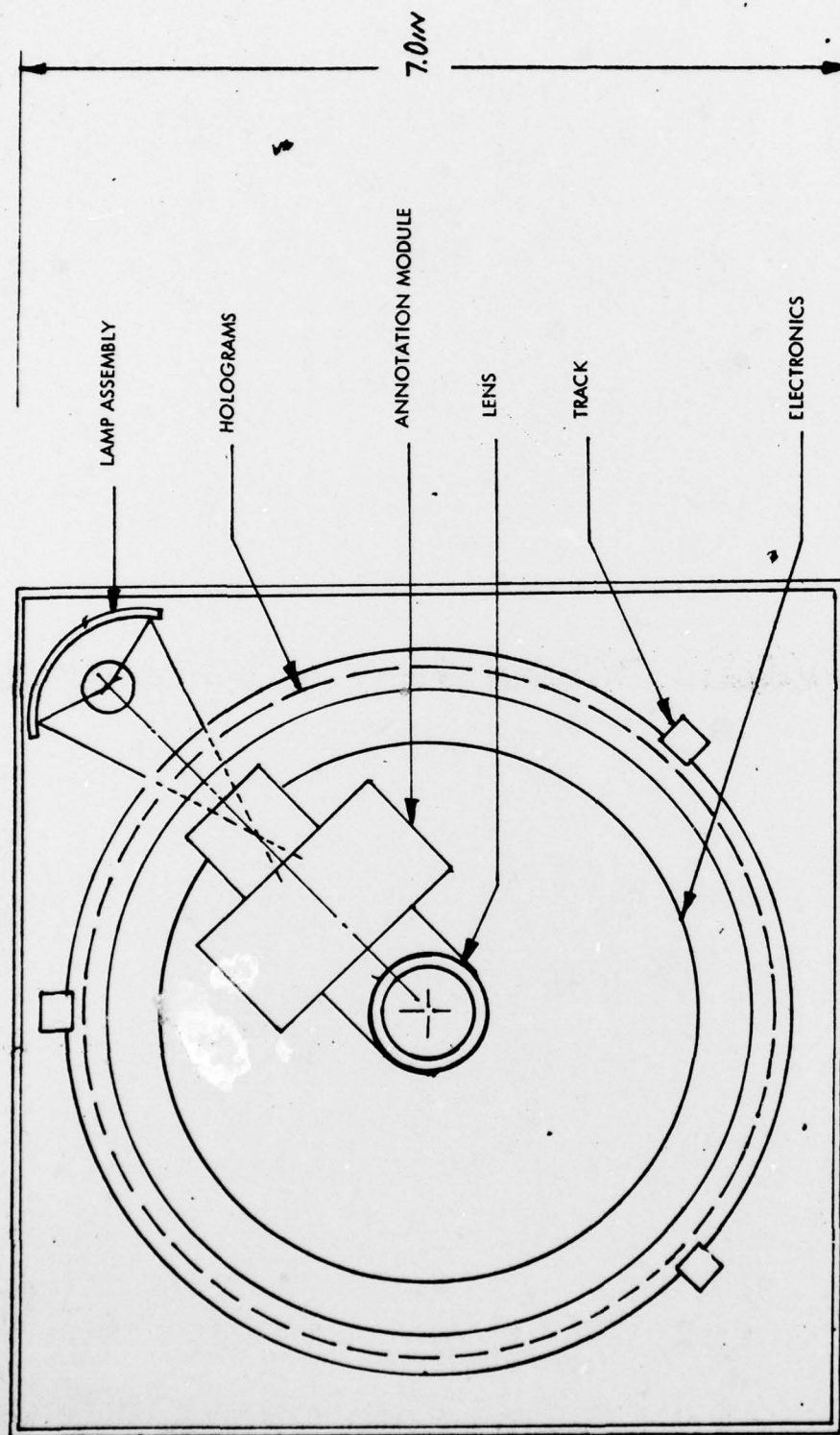


Figure 2-1 (b) Front view using diagonal lamp axis.

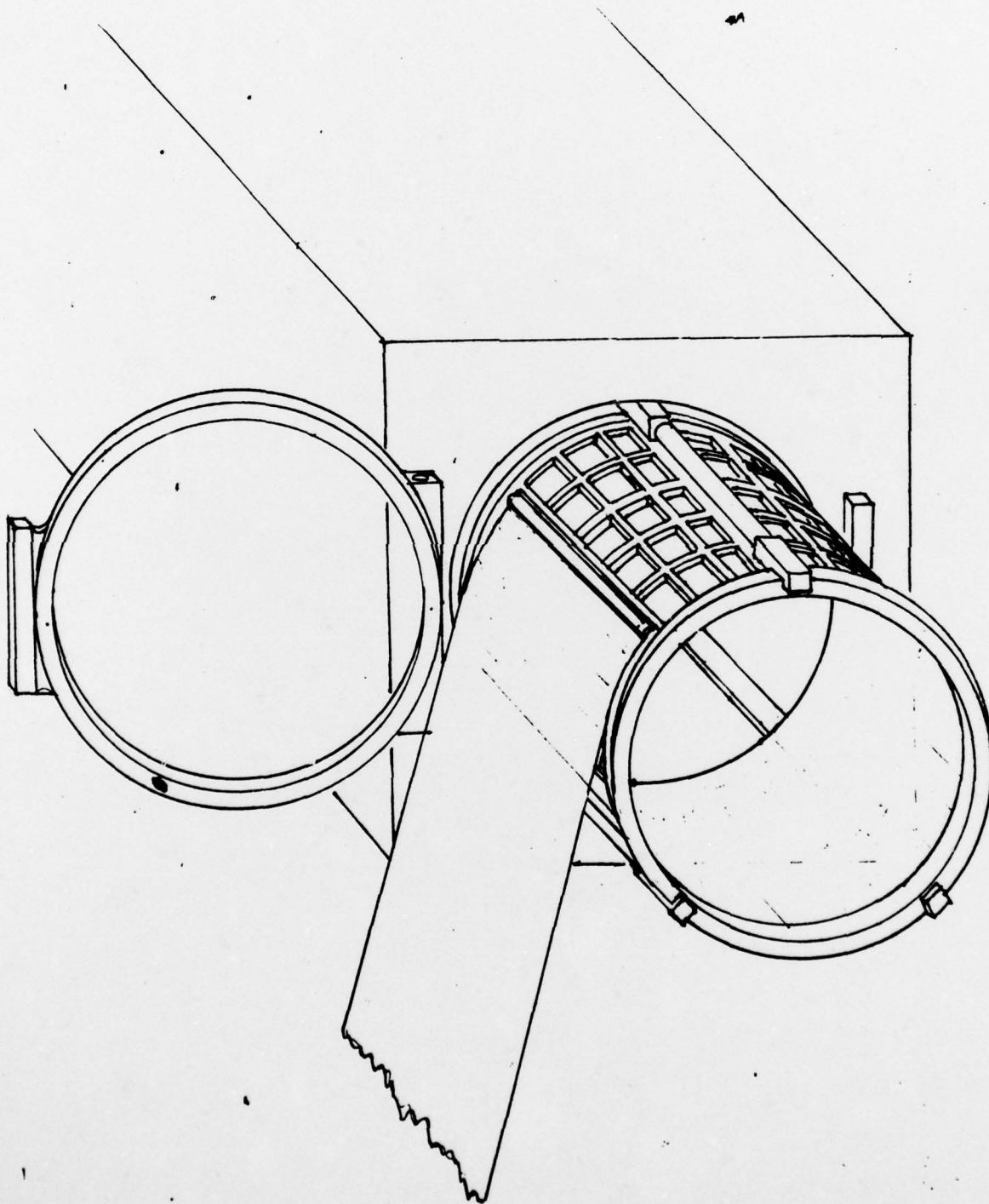


Figure 2-2. Loading the maps (accomplished by swinging the projection screen back, withdrawing the drum on its extendable tracks and attaching the fiche)